Material Flammability at Lunar and Martian Gravity

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FM^2 Background

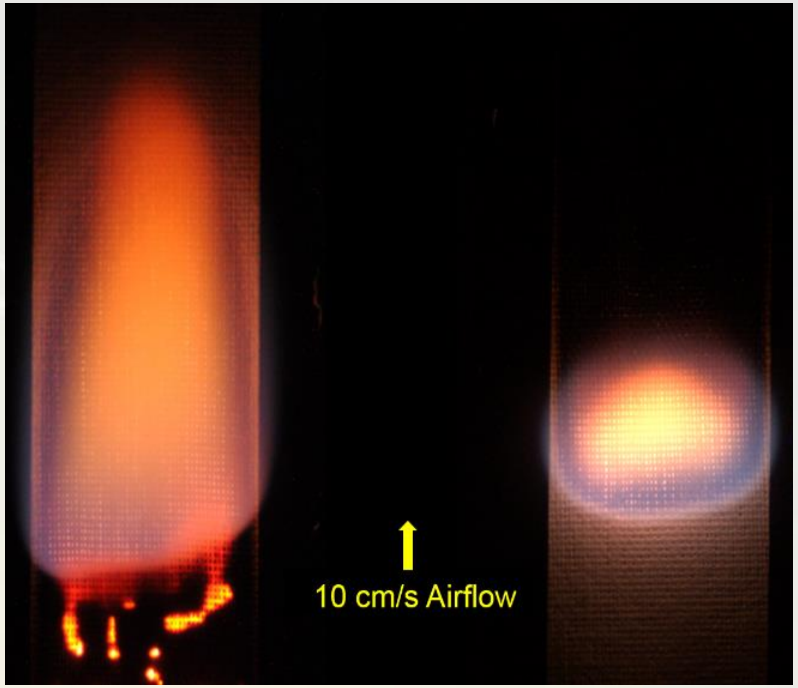
NASA relies on a 1-g test for screening material flammability for flight.

- Material ignited near bottom and flame spreads upward.
- If a material passes this test, then it is considered safe for spaceflight.
- If material fails, its use is restricted in time, quantity, etc.

This test has been a practical means to assess the great number of materials that have been screened.

However, microgravity research has suggested that normal gravity may not represent the most flammable condition for a material.

Theoretical and experimental results have demonstrated that some materials that will not burn in 1-g <u>will burn in 0-g</u> (with a low-speed flow) or in partial gravity (such as Lunar-g).



Flame Spread in Microgravity over 2.2-cm-wide SIBAL Fabric.

Left: Concurrent flow (comparable to 1-g upward spread).
Right: Opposed flow (comparable to 1-g downward spread).

In microgravity, both concurrent and opposed-flow flame spread are possible, but on Earth, downward flame spread (opposed flow) cannot be achieved.

This demonstrates enhanced limits of flammability in microgravity, and suggests similar behavior at partial gravity.

Background Summary

There is mounting evidence that if a material passes the NASA standard test it might fail at levels of gravity and flow below 1-g.

Experiments using drop towers and aircraft have provided valuable information but run into limitations.

Tests on the Moon will resolve some important questions and set the primary benchmark for future tests.

BPS replanning request

BPS management requested that the FM^2 experiment increase alignment with NASA's exploration needs.

Better alignment with NASA needs was previously identified as an opportunity in the Science Concept Review

The GRC science team agrees that the best opportunity to directly address a stakeholder needs would be to test a material being studied in Phase 3 of the HLS and NESC material flammability effort.

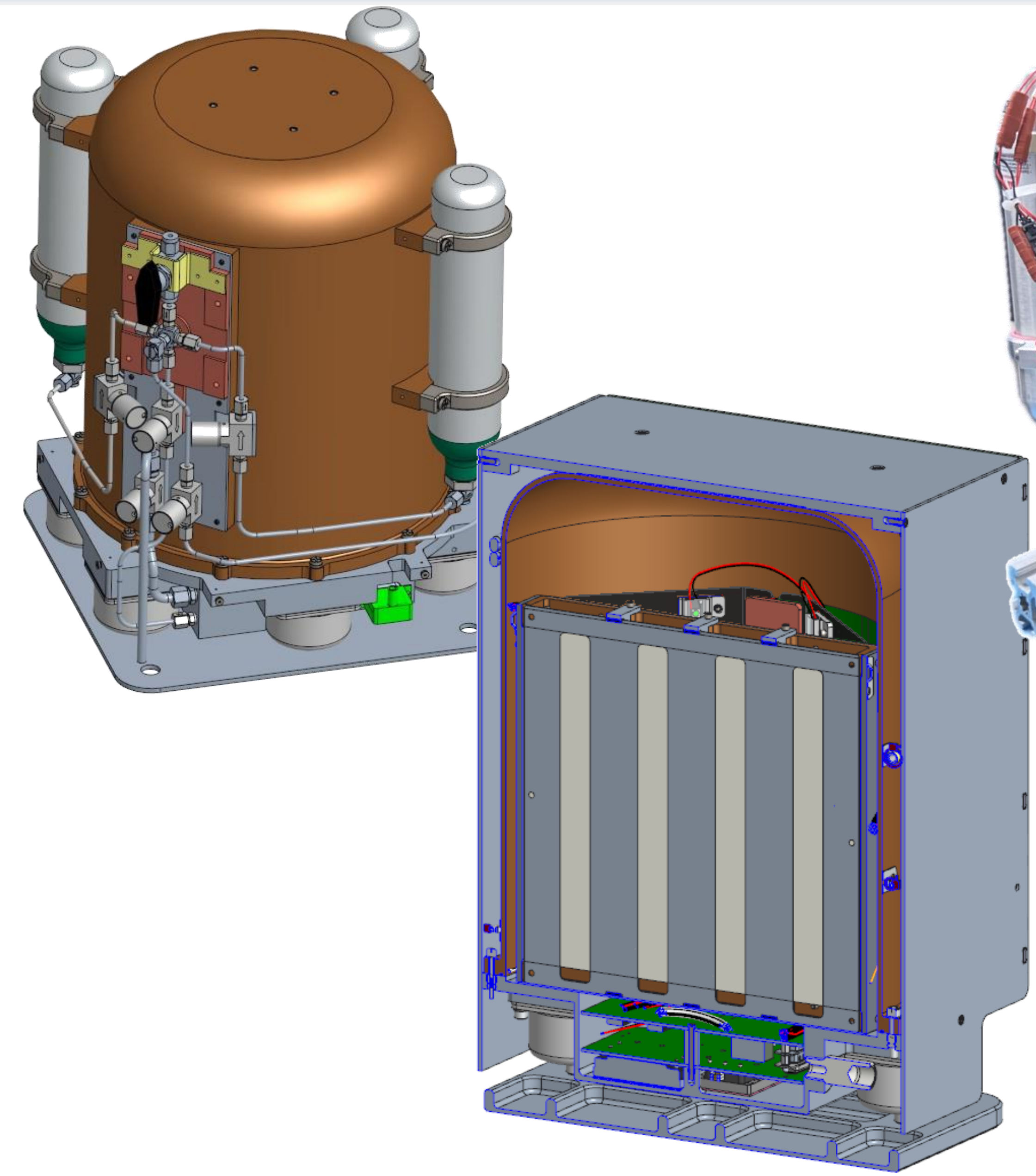
Current concept

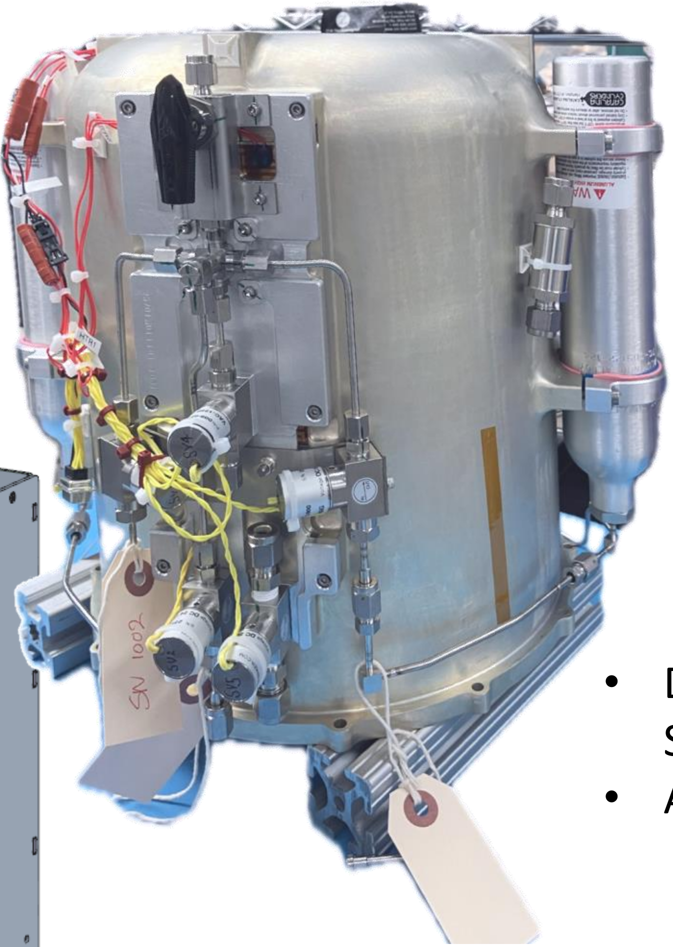
Test a material with an expected Lunar LOC of 24-26% and an expected oxygen consumption of 0.08 mol fraction

Conduct four tests at 8.2 psi:

1. Start at 37% *should burn to threshold*
2. Start at 33% *should burn to threshold*
3. Start at 29% *should burn to threshold*
4. Start at 25% *not expected to ignite but would provide a margin of safety if the limit was lower than expected.*

Flammability of Materials on the Moon (FM^2)

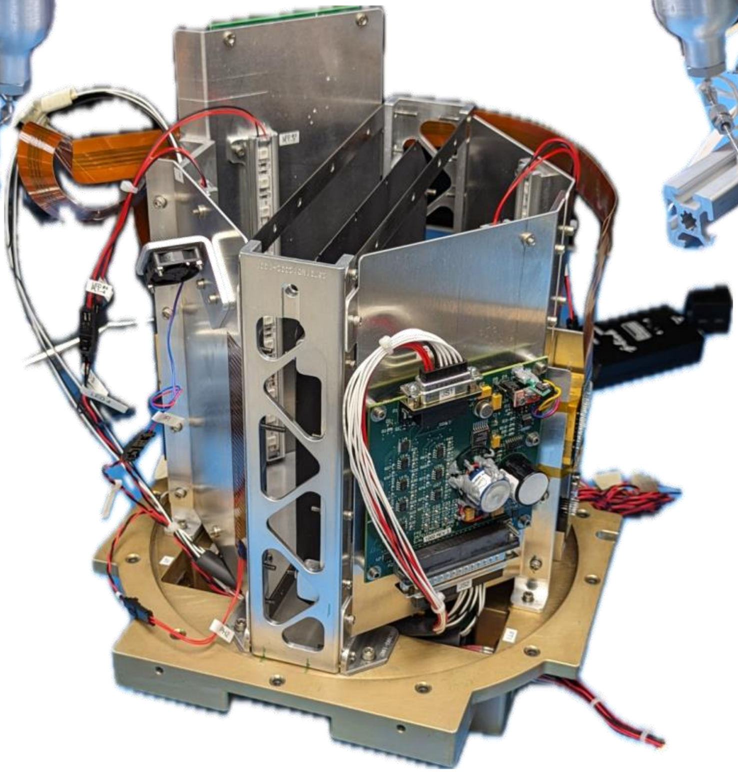


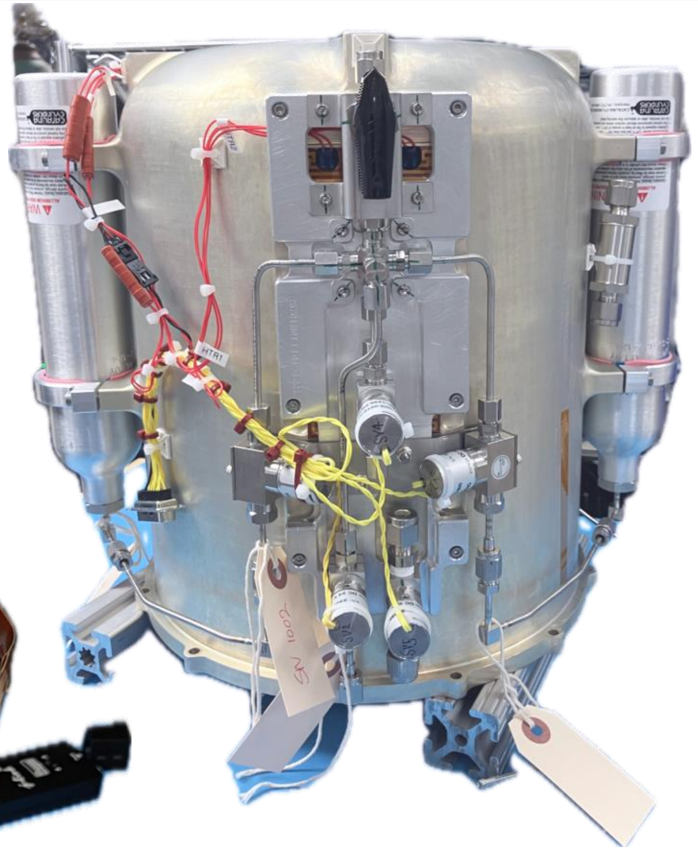


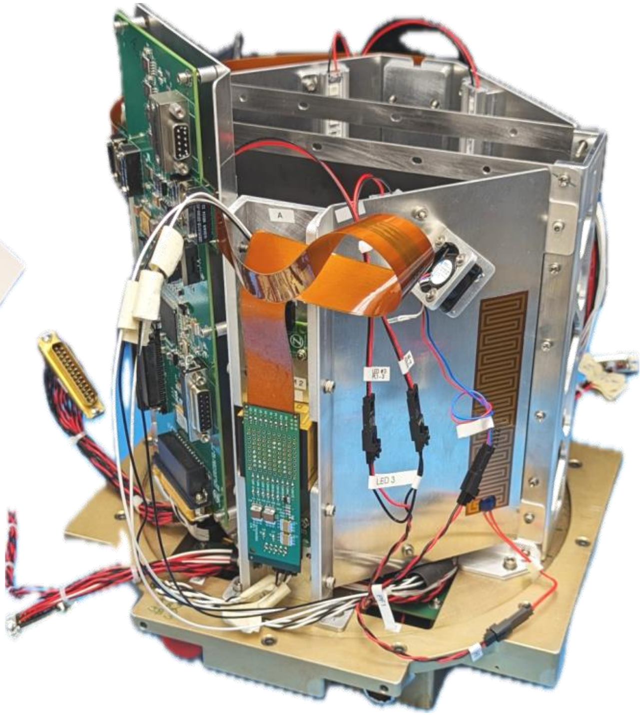
- Delivered to the Lunar Surface by the SpaceX uncrewed demo
- Atmospheric chamber:
  - Fill to different oxygen concentrations using gas cylinders
  - Chamber volume 14.4 L
- Four 20-cm tall fabric samples burned individually; atmosphere is refreshed between burns
- Cameras and gas sensors

Flammability of Materials on the Moon (FM^2)

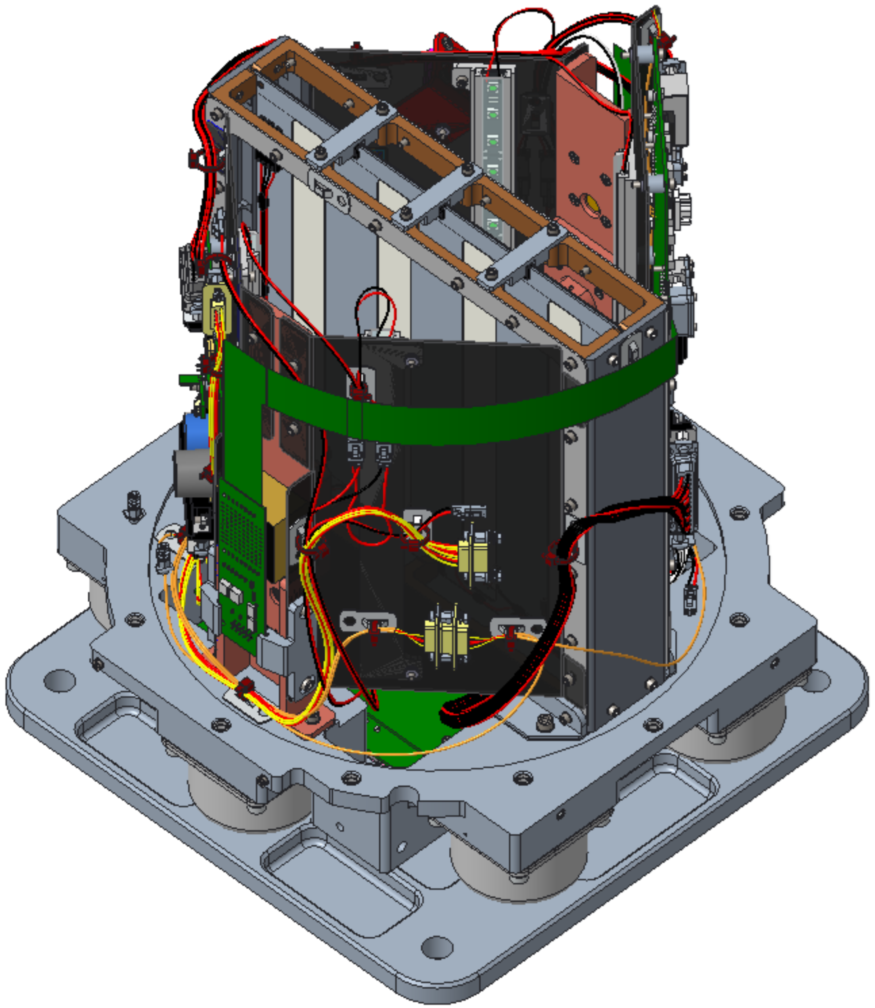
FM^2 Flight Engineering Model Photographs

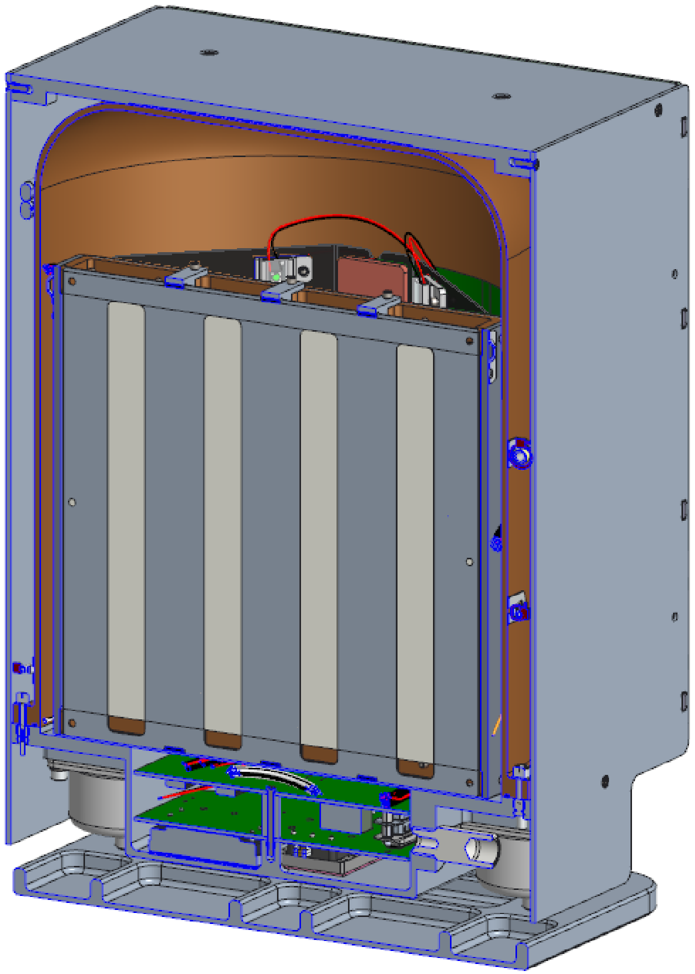






FM² Sample card concept





FM^2 Objectives

A. Conduct Lunar surface flammability tests that are important to NASA HLS (Human Landing System).

B. Conduct test to assist in validation of the Phase 3 testing in support of HLS and NESC program; Find flammability limit of 1 material per flight at 8.2 psia upward burning.

C. Evaluate the hypothesis that some materials burning in partial-g environments may be more flammable compared to 1-g.

   1. Obtain data on ignition, flame growth, extinction oxygen levels, and flame spread over solid materials in Lunar gravity and compare to 1-g results.
   2. Understand how partial gravity changes the solid-gas interactions.

D. Provide a bridge between the current 1-g material screening method and actual behavior in reduced gravity.

FM^2 Science Requirements: Chamber and Fuel

Initial Chamber Conditions

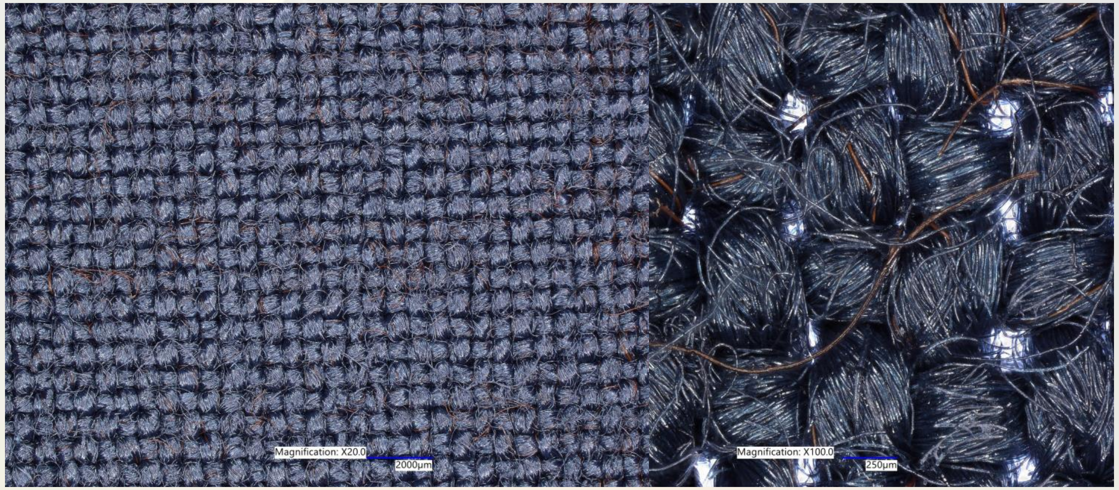
Each of the four tests requires its own chamber initial atmosphere as follows with venting to vacuum between tests:

Test 1: 8.2 psia (+/- 0.3 psi), 37% O_2 , balance nitrogen)
Test 2: 8.2 psia (+/- 0.3 psi), 33% O_2 , balance nitrogen)
Test 3: 8.2 psia (+/- 0.3 psi), 29% O_2 , balance nitrogen)
Test 4: 8.2 psia (+/- 0.3 psi), 25% O_2 , balance nitrogen)

Fuel and mounting

Fabric sheets (Synergy Pro "Navy") mounted between thin metal frames

Expose 2 cm (+/- 0.05 cm) x 20 cm (+/- 0.2 cm) of both sides of the sheet



Ignition

Hot wire igniter for each individual sample (currently ignites the bottom for upward burns, but could be changed)

FM² Science Requirements: Imaging and Diagnostics

Two Camera views (at least 20 frames/s)

A camera viewing the front of the samples.

A camera viewing the back of the samples.

Chamber Illumination

Sample illumination for several frames at a regular interval (e.g. every 5 seconds).

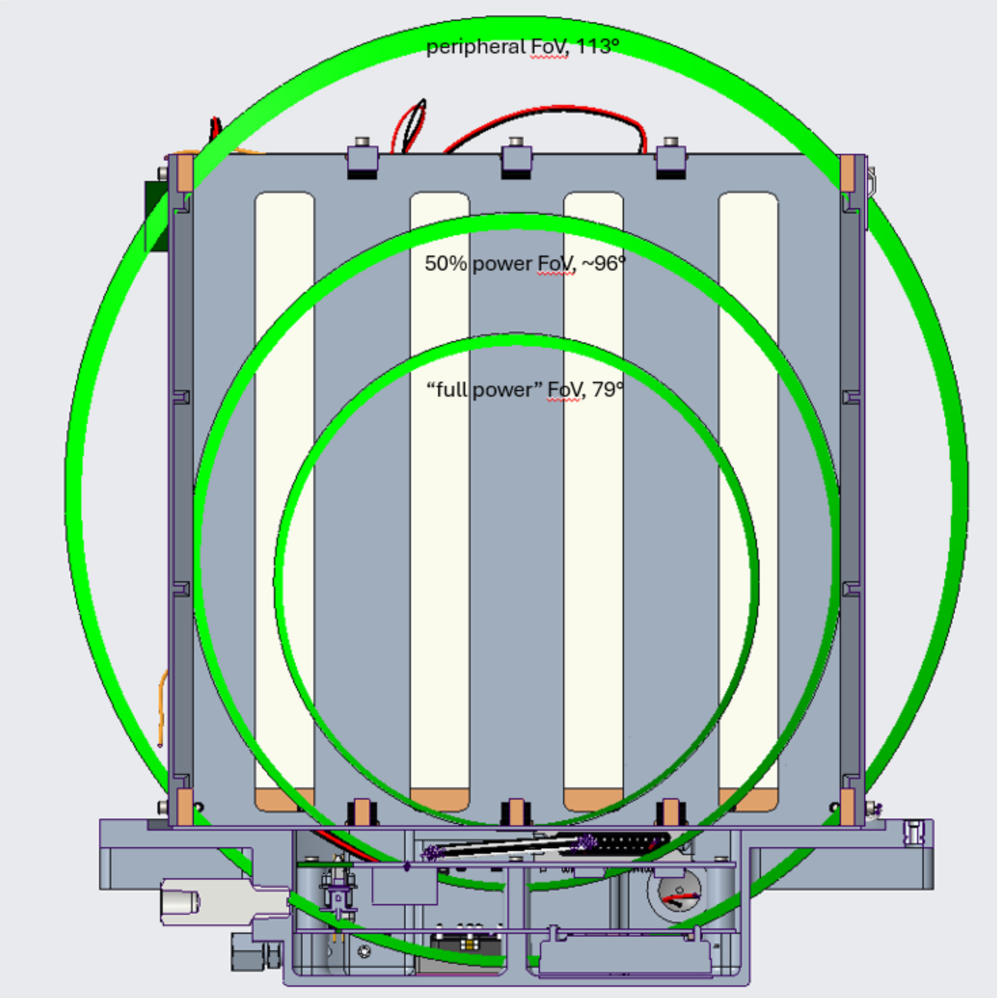
Radiometers

Two radiometers view the front and back of the samples.

Gas sensors

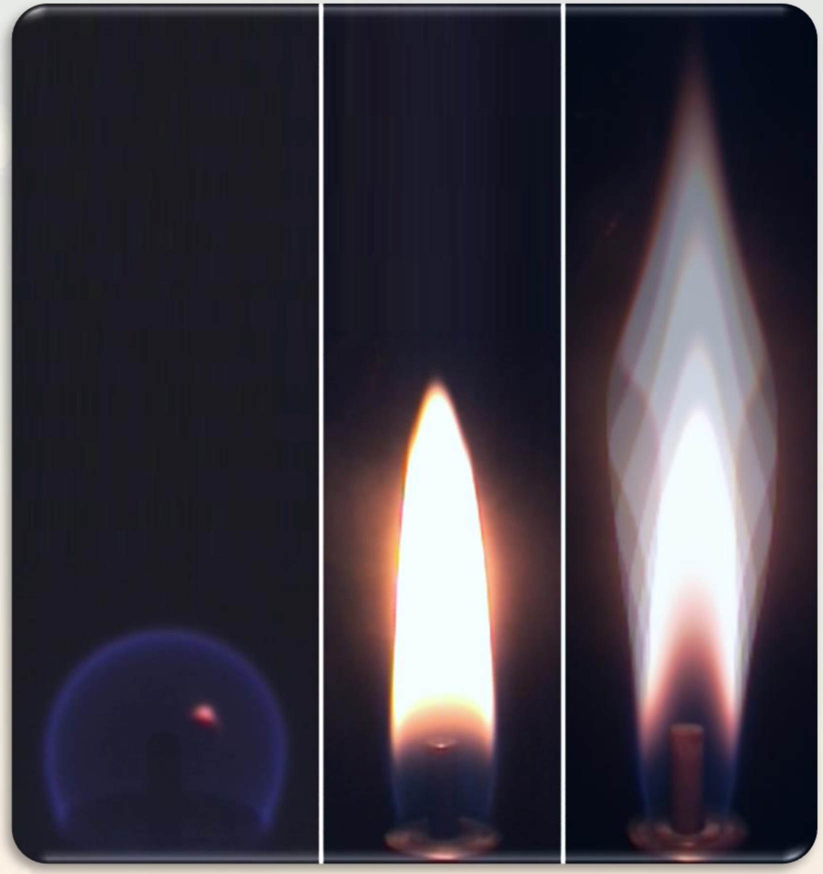
Oxygen, carbon dioxide, carbon monoxide, humidity

Record during burn and for one minute (± 5 s) immediately before and right after.



FM^2 Summary

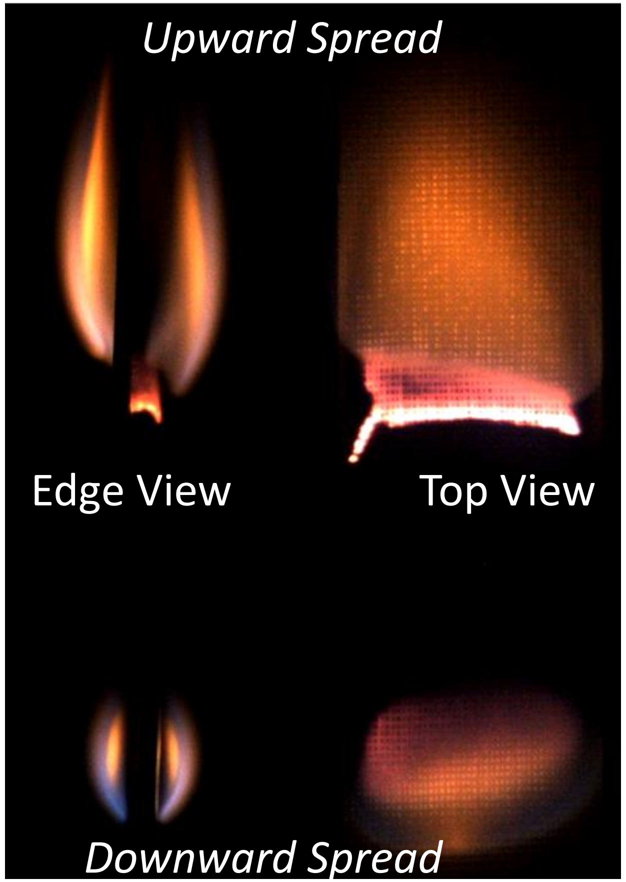
- Normal gravity may not be the most flammable condition.
- Drop towers and aircraft are limited by duration and/or Coriolis force effects.
- FM^2: First-ever observations and measurements of flame spread on the Moon.
- Provide a bridge between 1-g and future partial-g environments.

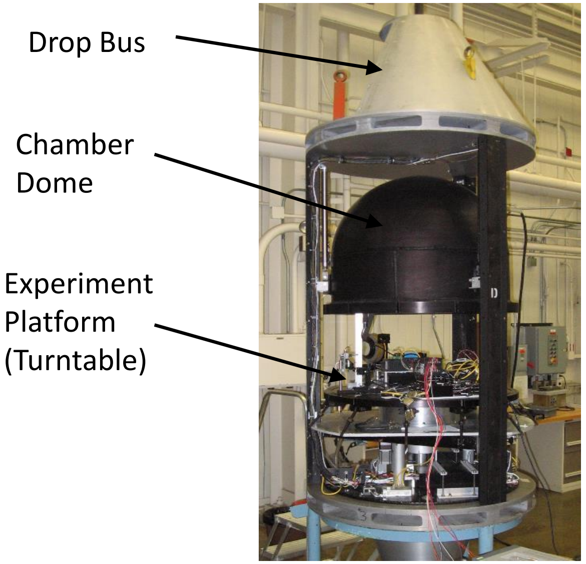


0-g Lunar-g 1-g

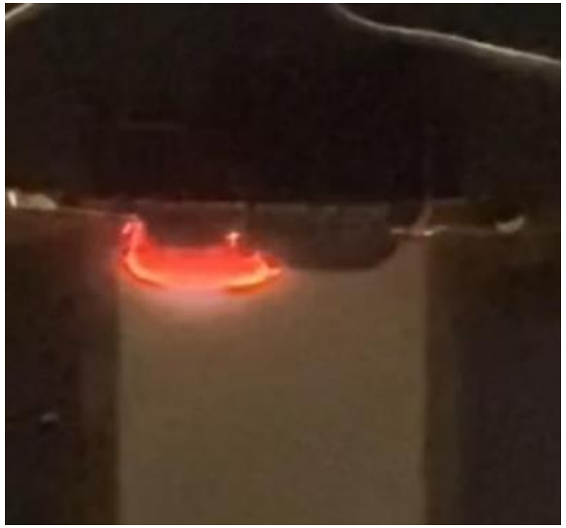
2-cm-wide SIBAL fabric burning in Lunar-g

Conditions: Air, 1 atm
(Playback is at 1/3 speed)





Lunar-g = 0.165 g_E



Normal g

Suggested Approach

Identify small number of candidate samples from Phase 3 matrix.

Conduct tests at GRC in centrifuge and flow tunnel combined with WSTF testing to down select to one material.

Conduct upward flammability tests with up to 4 samples

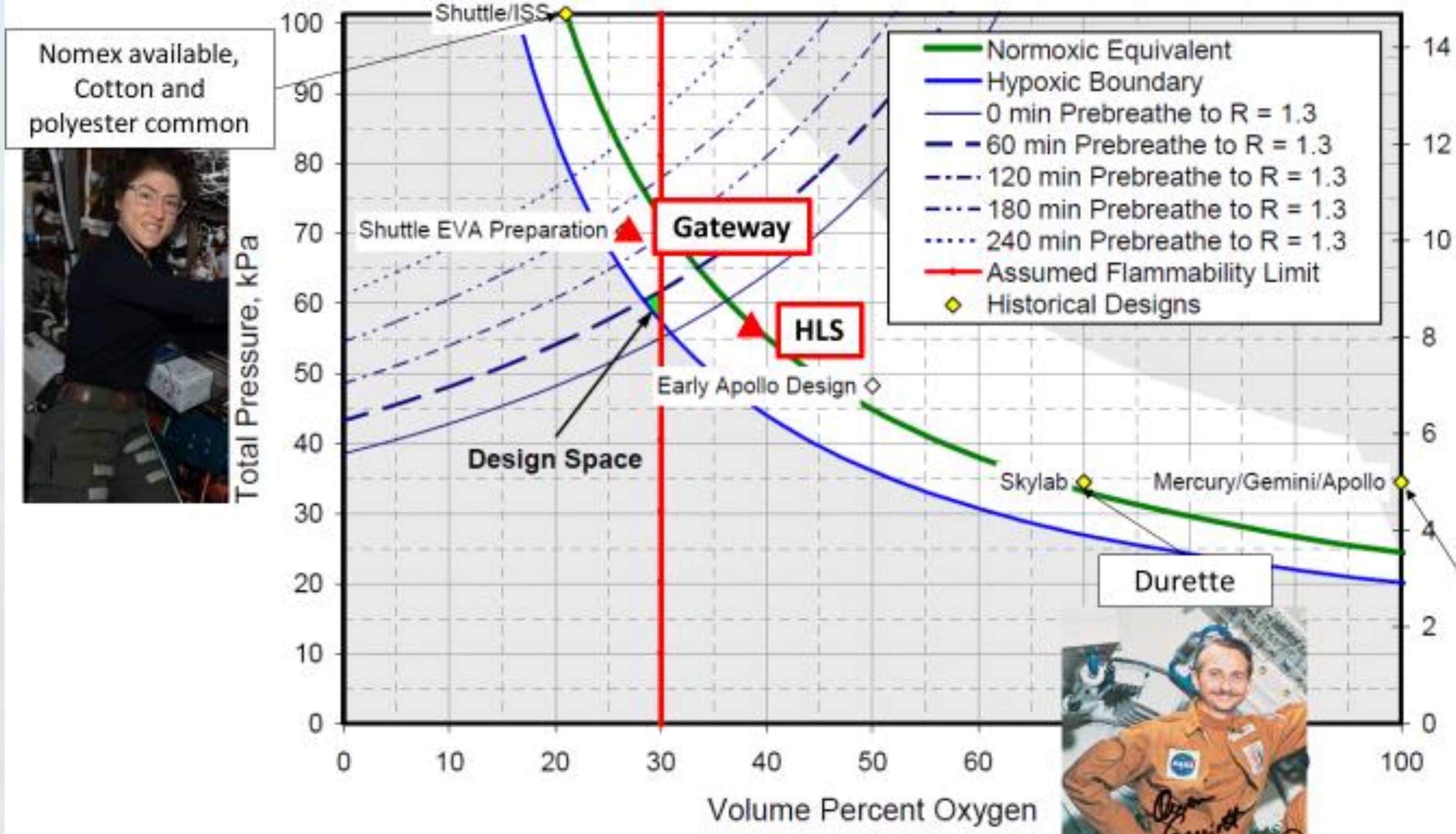
FM^2 hardware does not support ignition approaches used at WSTF or in Centrifuge. (flow change, oxygen change)

Expect oxygen concentration to decrease by up to 0.08 mol fraction in a test.

This will enable "scanning" to the limit allowing easier ignition since the atmosphere will be more flammable

Material	Category	Usage	Program	Priority
Ortho 116	Textile	Suit EPG (outermost layer)	EHP/xEVAS	EHP 1st
Rubber, Silicone LT Blue (RTV630)	Elastomer	EMU Boot	EHP/xEVAS	EHP 2nd
Natural Synergy Pro	Textile	CTBs, sleeping bag	HLS/GFP	HLS 1st
Black PBI Max	Textile	Crew Clothing, sleeping bag	HLS/GFP	HLS 2nd
Fabric, Teflon, Bleached	Textile	Suit Glove Back	EHP/xEVAS	
Nomex	Textile	PR Inner walls, etc	EHP/PR	
Kevlar Webbing Sturges 34515	Textile	Mobility Aid	HLS/GFP	
Rubber, Silicone Conformal Coat RTV3140	Elastomer	Avionics boxes, etc	EHP/PR	
Kynar 720 PVDF Film 3 mil	Elastomer	GFP trash bag	Both	
TC380 Sandwich	Hard Plastics	Blue Floors	HLS/GFP	
P212 tape on substrate	Tape	Overwrap Tape	Both	
Kapton with silicone adhesive	Tape	Overwrap Tape	Both	
M22759/82-22-9 Nickel Plated Copper Wire with PTFE/Polyimide Insulation	Wires	Electrical Wiring	Both	
PVC wiring	Wires	Electrical Wiring	Both	

Saturation Atmosphere	Microgravity Prebreathe (h:mm)
14.7 psi, 21% O_2	4:00
10.2 psi, 26.5% O_2	~2:40 (ISLE)
8.2 psi, 34% O_2	**0:00-0:15**
5.0 psi, 100% O_2 (Apollo, Gemini)	0:00



Bounding the spacecraft atmosphere design space for future exploration missions. Kevin E. Lange, Alan T. Perka, Bruce E. Duffield, Frank F. Jeng. NASA/CR-2005-213689

Table 2: NASA-STD-6001B Flammability Test 1 Maximum Oxygen Concentration Sample Length Impact

	Sample Length cm	in.	Pressure psia	ULOI[a]	MOC[b]
Solimide TA-301	15	6	10.2	25.6	22.0
	18	7	10.2	25.2	23.0
	20	8	10.2	24.7	23.0
	30	12	10.2	24.3	23.1
Ultem	18	7	10.2	25.8	23.1
	20	8	10.2	24.0	23.1
	30	12	10.2	24.5	23.0
Nomex HT 90-40 (Hemmed)	15	6	10.2	28.5	25.0
	18	7	10.2	29.3	25.0
	20	8	10.2	29.8	25.0
Nomex HT 90-40 (Unhemmed)	15	6	10.2	25.9	24.1
	18	7	10.2	26.1	24.1
	20	8	10.2	25.4	24.0
	30	12	10.2	25.8	23.1
NX2245	15	6	10.2	26.2	25.0
	18	7	10.2	26.3	25.0
	20	8	10.2	27.6	25.0
	30	12	10.2	26.5	25.1

[a] ULOI (Upward Limiting Oxygen Index) is a variation of ASTM D28632 Limiting Oxygen Index (LOI) utilizing the NASA-STD-6001B test fixture and orientation

[b] MOC (Maximum Oxygen Concentration) per NASA-STD-6001B, Test 1

All O_2 Concentration measurements were made to a tolerance of +0.15%/-0.0 %

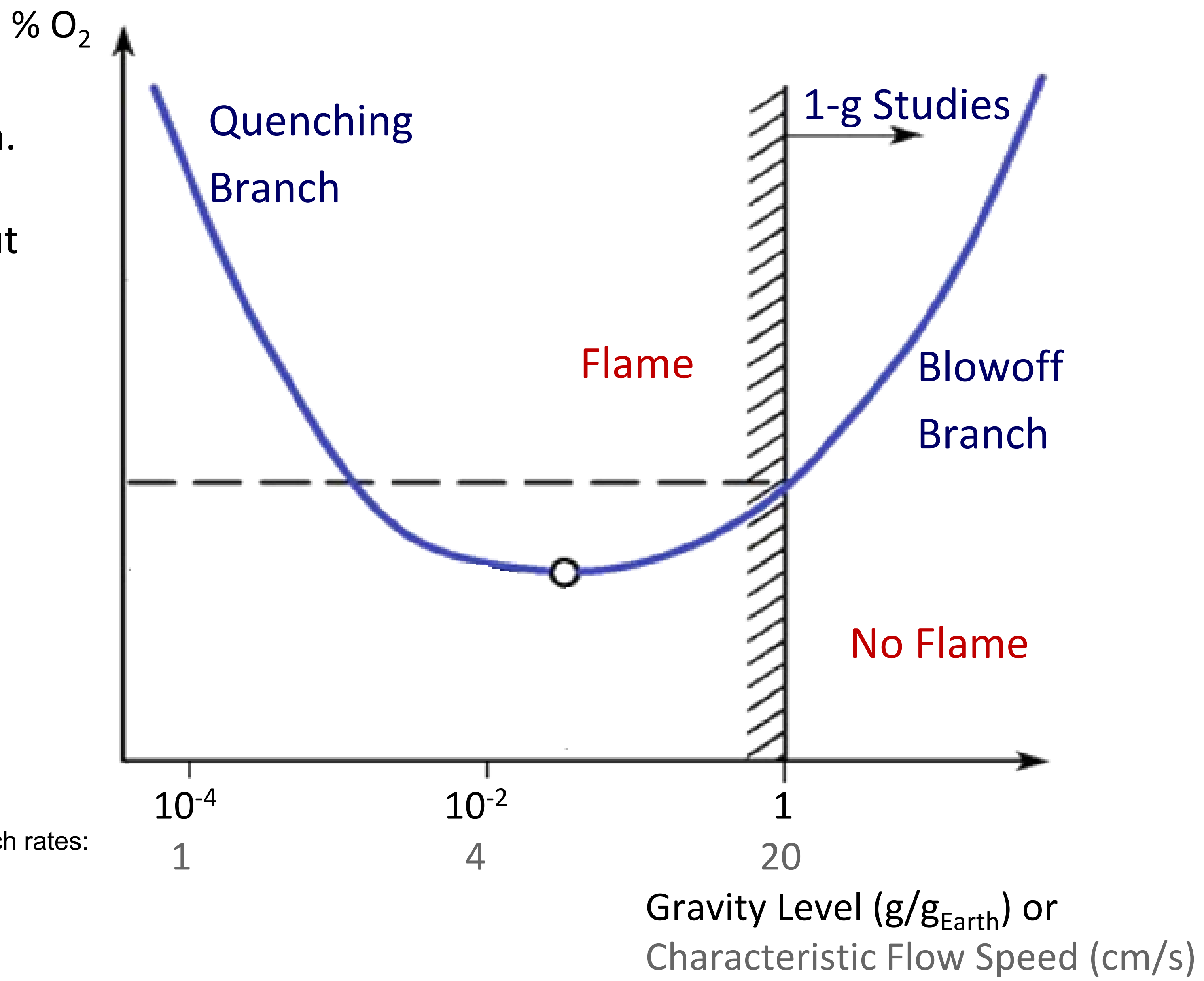
From "NASA-STD-6001B Test 1 Upward Flame Propagation; Sample Length Impact on MOC Investigation," Susana Tapia Harper, Alfredo Juarez, Brenton L. Woods, and Harold D. Beeson, 47th International Conference on Environmental Systems (2017)

Flammability Boundary

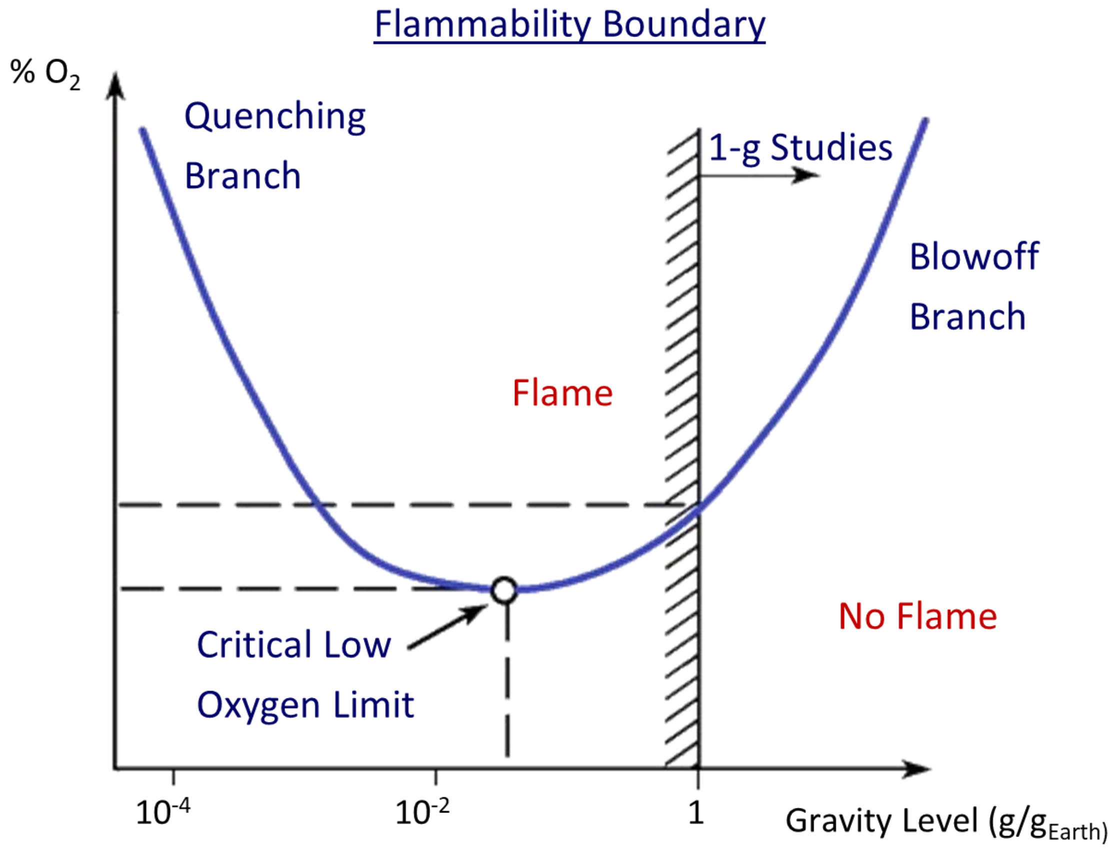
Flow: Buoyancy, forced convection, or both.

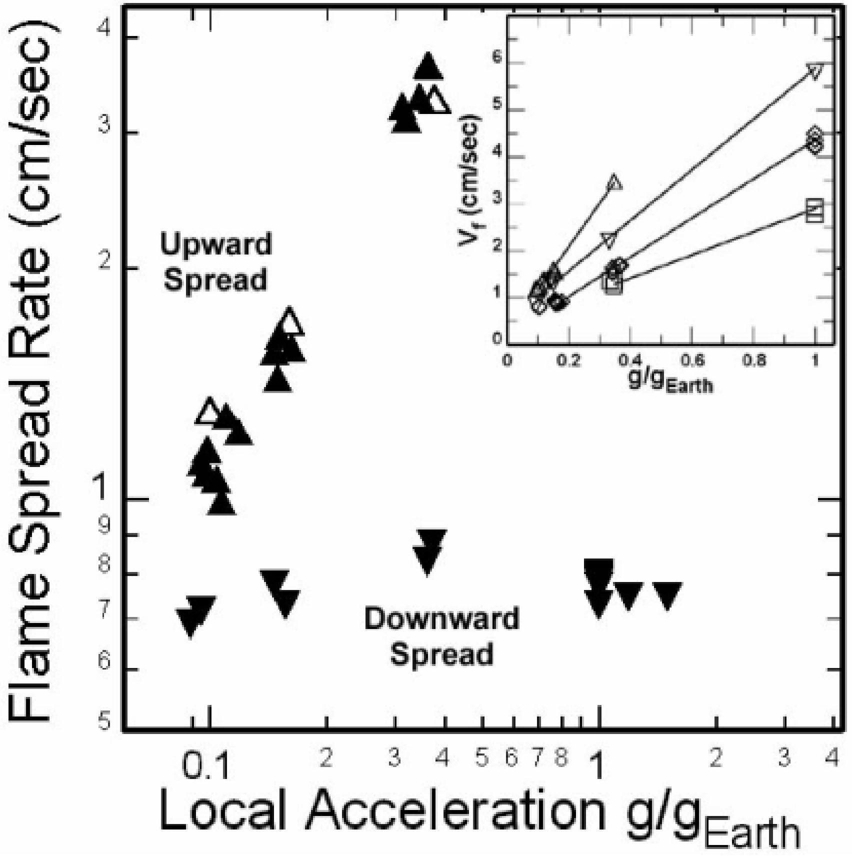
Most experiments: Tests in microgravity but with imposed forced convection.

Lunar surface: Unlimited duration to study flame spread and flammability.



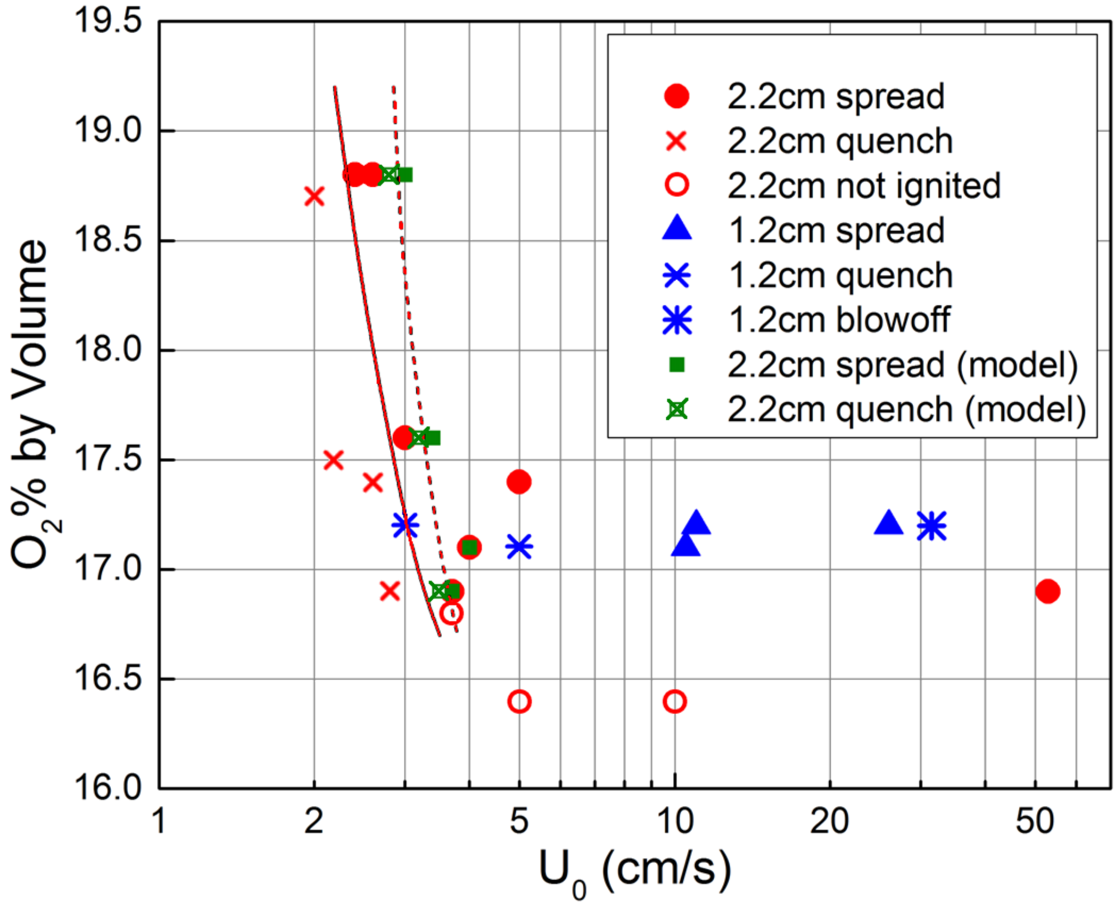
Reference: T'ien, J. S., Diffusion flame extinction at small stretch rates: the mechanism of radiative loss, *Combustion and Flame*, 1986.





- Numerical and experimental evidence suggests that Lunar gravity is nearly the most flammable condition.
- Oxygen concentration for flammability reaches a minimum value in the vicinity of $g = g_{Moon}$ (left; model)
- Downward flame spread rate peaks in partial-g [right, Sacksteder; KC-135 experiments].

Flammability Boundary for SIBAL fabric from ISS experiments (Zhao et al.)

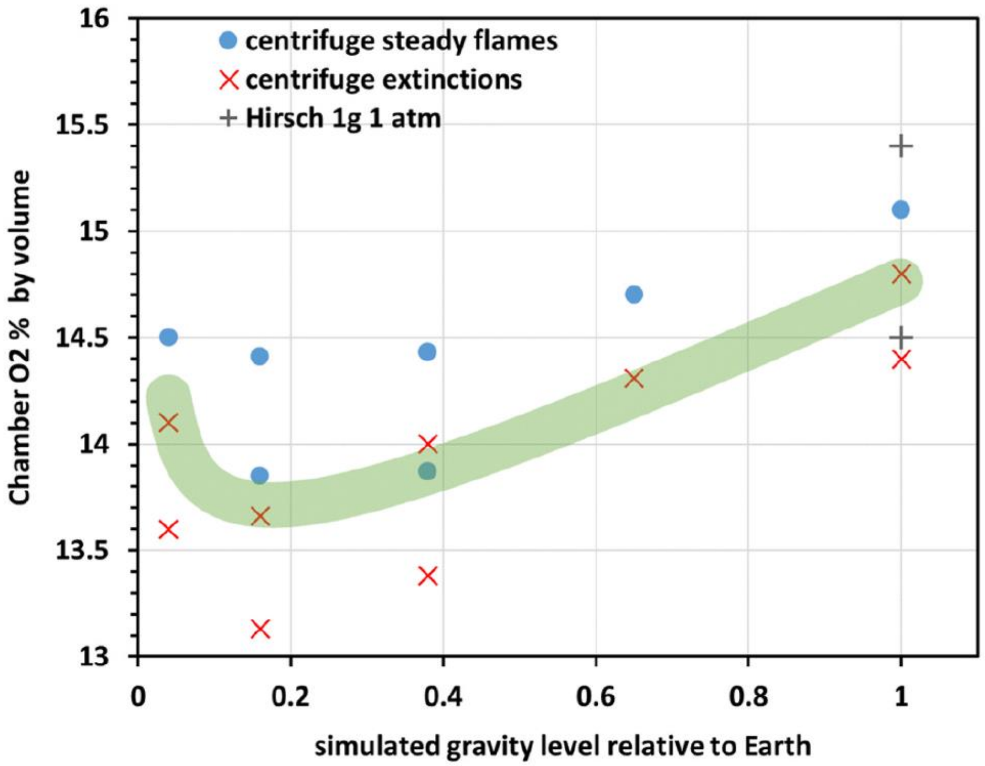


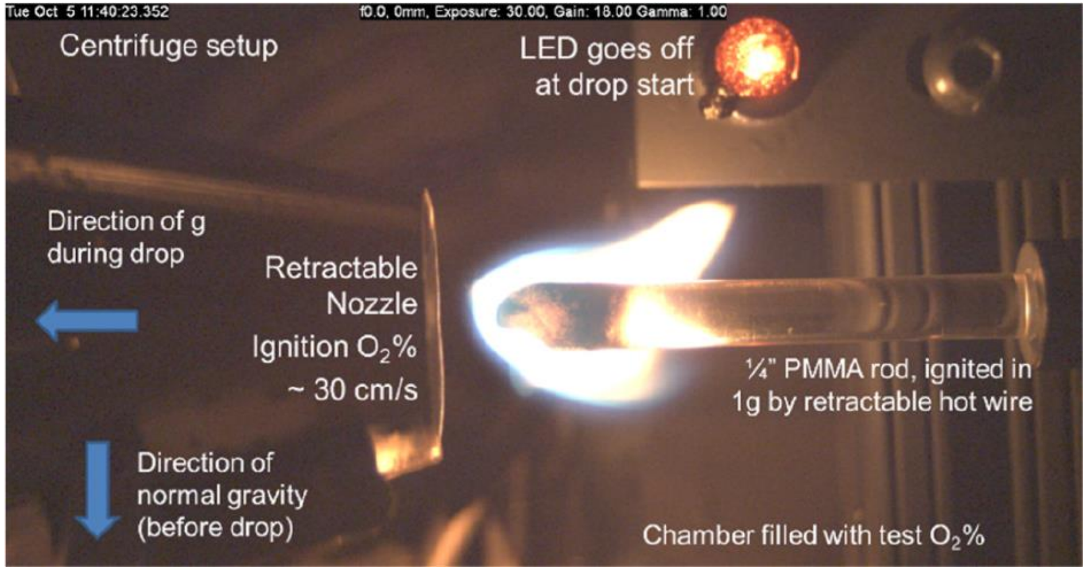
Quenching boundary for SIBAL fabric in concurrent flow in microgravity.

Solid and dashed lines are the experimental and computational quenching boundaries for the 2.2 cm sample.

From: Concurrent flame growth, spread, and quenching over composite fabric samples in low speed purely forced flow in microgravity, Xiaoyang Zhao, Ya-Ting T. Liao, Michael C. Johnston, James S. T'ien, Paul V. Ferkul, Sandra L. Olson, Proc. Comb. Inst. 36 (2017)

Flammability Boundary for upward-burning PMMA rods in centrifuge (Olson et al.)



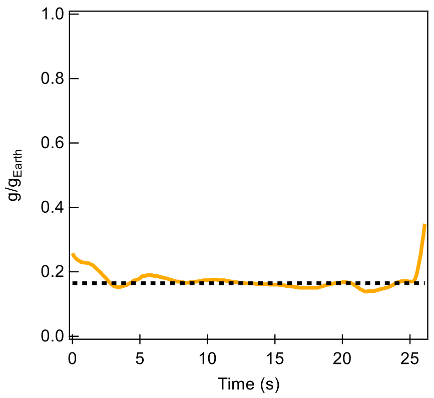


- Extinction boundary shaded in green that divides steady flames from extinguished flames in centrifuge drop tests.
- Drop tower limits experiment time to ~5 s. Gas phase response time may be short enough, solid time typically too long.

From: "Partial gravity flammability of cast PMMA rods in concurrent axial stagnation flow," S.L. Olson, E.S. Neumann, V.M. Valletta, A.L. Ogorzaly, J.C. Owens, Fire Safety Journal 150 (2024) 104267.

Parabolic Flight Aircraft Testing at Lunar-g

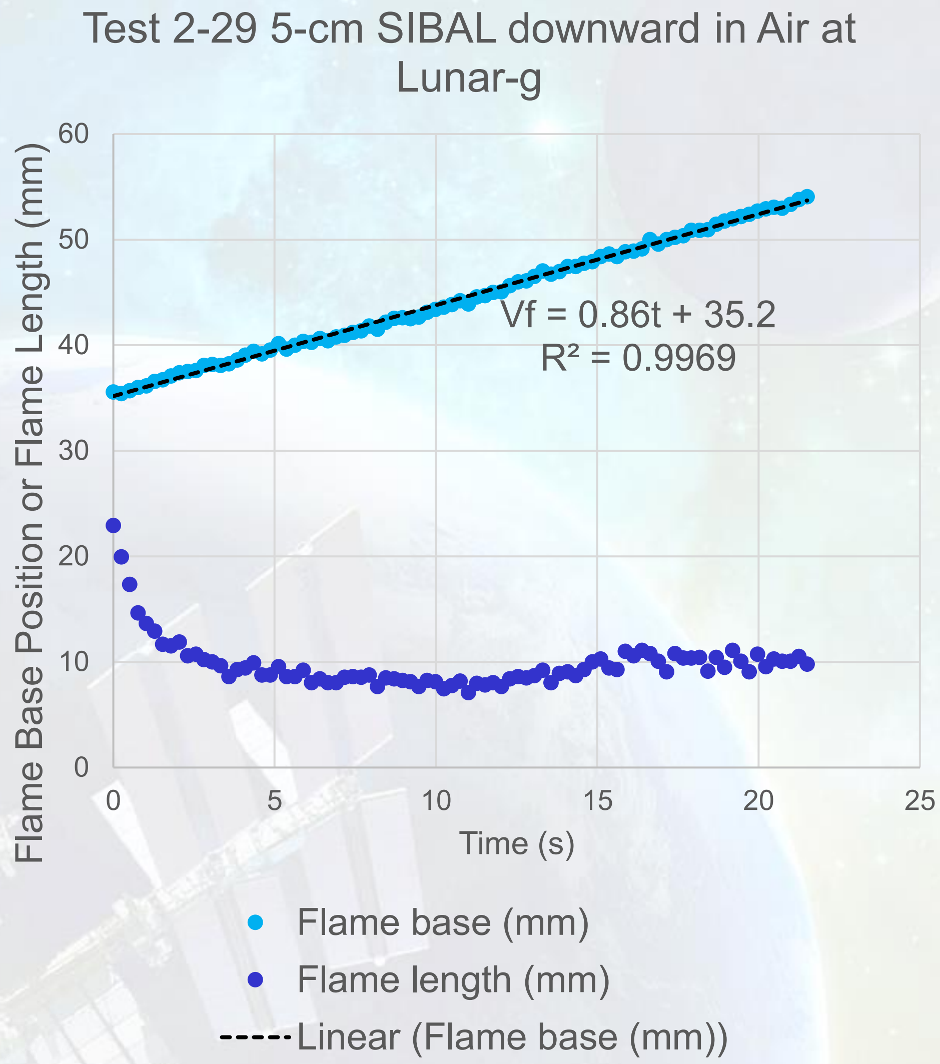
SIBAL, 5 cm wide, Lunar g, 21% O_2, 1 atm
Day 2, Parabola # 29



$0.165g_{Earth}$

Lunar gravity: Steady, downward spread occurs for the entire 20-sec test time.

Parabolic Flight Aircraft Testing at Lunar-g

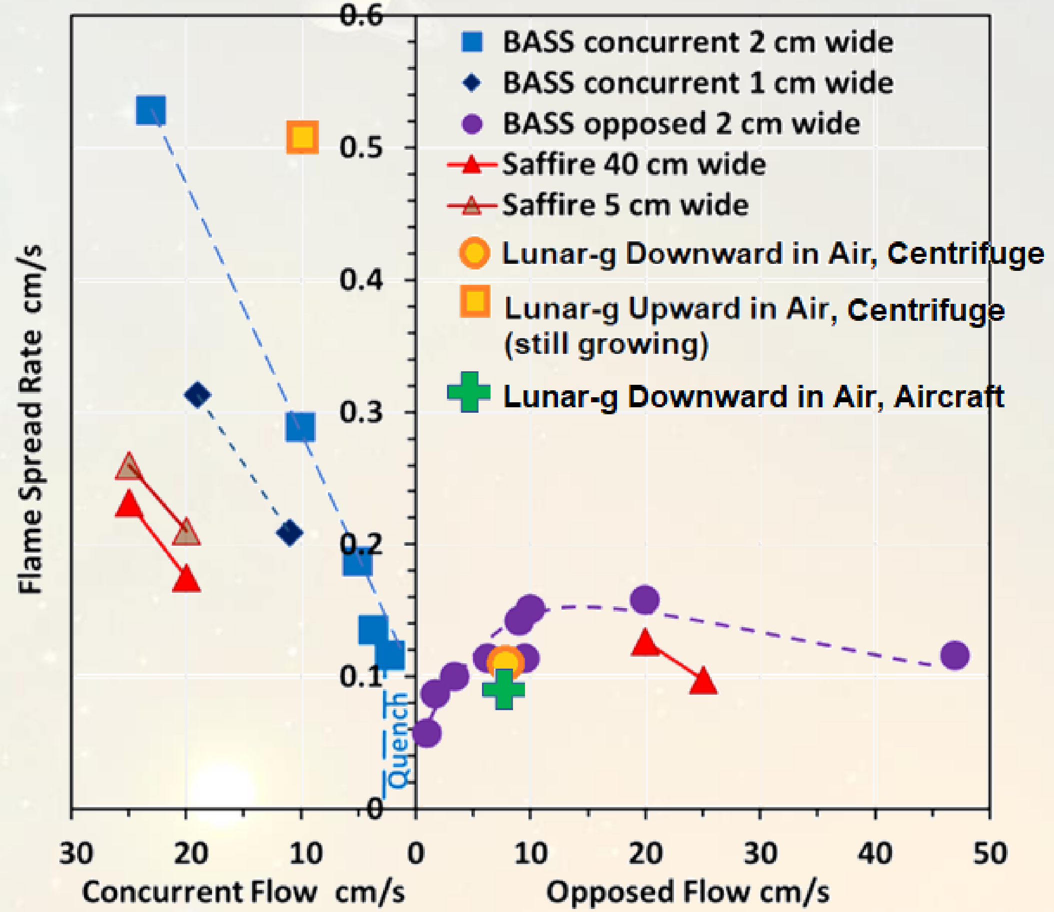


SIBAL Lunar-g downward burning <u>drop test with centrifuge</u>

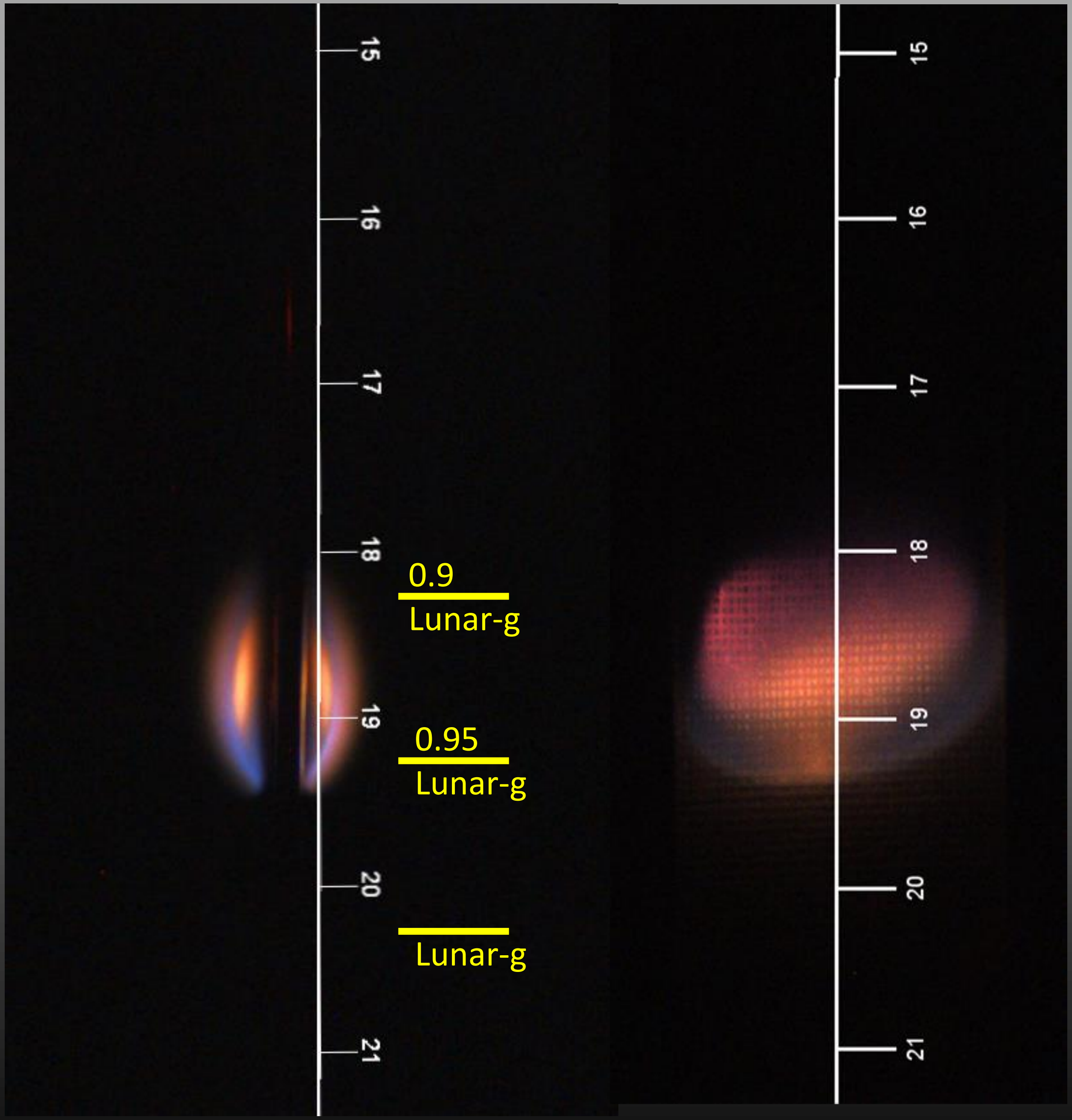
- Flame base spread rate in air: 0.11 cm/s

SIBAL Lunar-g downward burning <u>aircraft test</u>

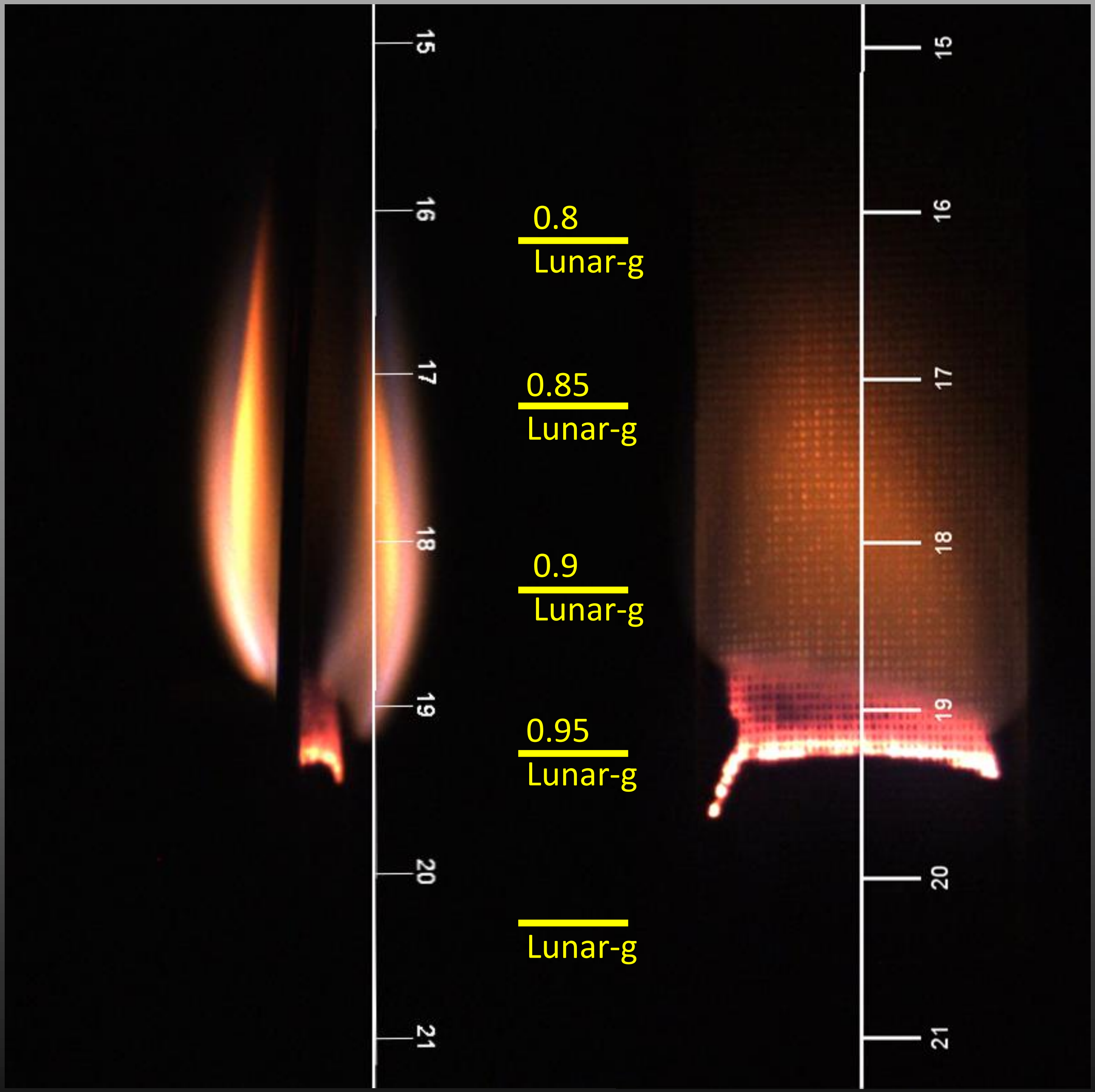
- Flame base spread rate in air: 0.086 cm/s

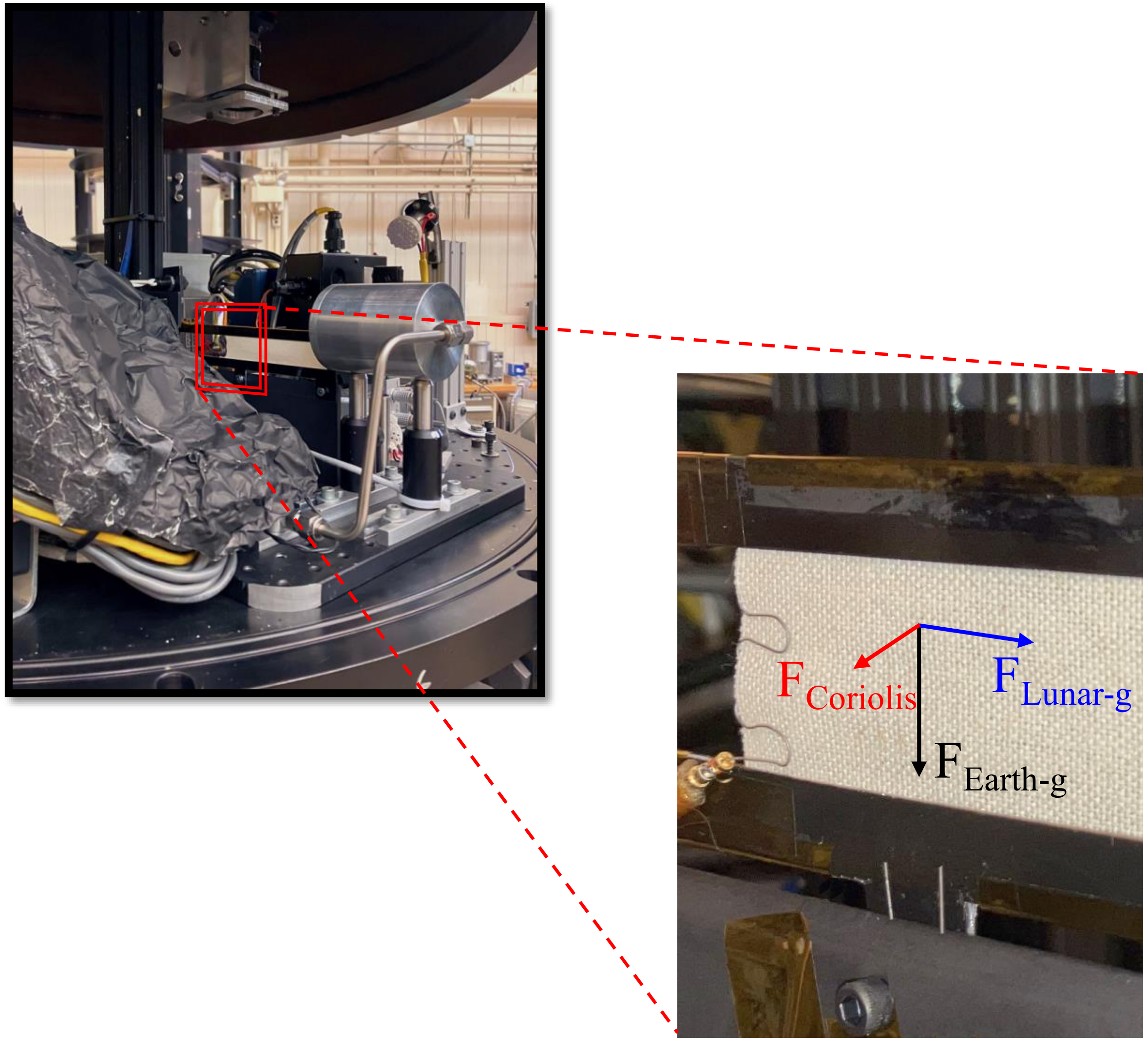


Downward Spread



Upward Spread





Forces acting on flame
(Fabric sample shown is 2 cm wide)

NASA's focus on exploration goals will dictate the required cabin atmosphere

- Very frequent EVAs are required to meet mission goals. 100% $O_{2,}$ 4.3 psia (to bend fingers, arms).
- HLS, Lunar habitat and pressurized rover will nominally use 8.2 psia / 34% O_2, 66% N_2 to "engineer-out" risk of decompression sickness.
- *Control bands* are expected to allow up to 37% O_2

Saturation Atmosphere	Microgravity Prebreathe (h:mm)
14.7 psi, 21% O_2	4:00
10.2 psi, 26.5% O_2	~2:40 (ISLE)
8.2 psi, 34% O_2	**0:00-0:15**
5.0 psi, 100% O_2 (Apollo, Gemini)	0:00

- *Humans* respond well to constant oxygen partial pressure (even at reduced total pressure),
- *Fire* responds to total oxygen concentration
- Fire risk sets the maximum oxygen boundary
- Fire safe materials become increasingly difficult to find as the oxygen concentration increases.

Post combustion vent gases for FM2 on CLPs

PMMA rod in 34% O_2 balance N_2 at 8.2 psi (2 tests)

PMMA; 34% O_2; 8.2 psi; up to 1.2 g burned			
Final O_2 fraction	13% to 21%	Vented Mass O_2, g	1.44 to 3.70
Final N_2 fraction	77% to 79%	Vented Mass N_2, g	6.3
Final CO_2 fraction	0 to 7.3%	Vented Mass CO_2, g	0 to 2.51
Final CO fraction	0 to 0.3%	Vented Mass CO, g	0 to 0.080
Final H_2O fraction	0 to 3.1%	Vented Mass H_2O, g	0 to 0.86
Soot produced	1 to 12 mg	Soot vented	~ 0 (filtered)

SIBAL fabric in 21% O_2 balance N_2 at 14.7 psi (2 tests)

SIBAL fabric; 21% O_2; 14.7 psi; up to 0.54 g burned			
Final O_2 fraction	17.5% to 21%	Vented Mass O_2, g	3.45 to 4.09
Final N_2 fraction	78% to 79%	Vented Mass N_2, g	13.5
Final CO_2 fraction	0 to 3.2%	Vented Mass CO_2, g	0 to 0.87
Final CO fraction	0 to 0.03%	Vented Mass CO, g	0 to 0.0056
Final H_2O fraction	0 to 1.4%	Vented Mass H_2O, g	0 to 0.30
Soot produced	1 to 5 mg	Soot vented	~ 0 (filtered)

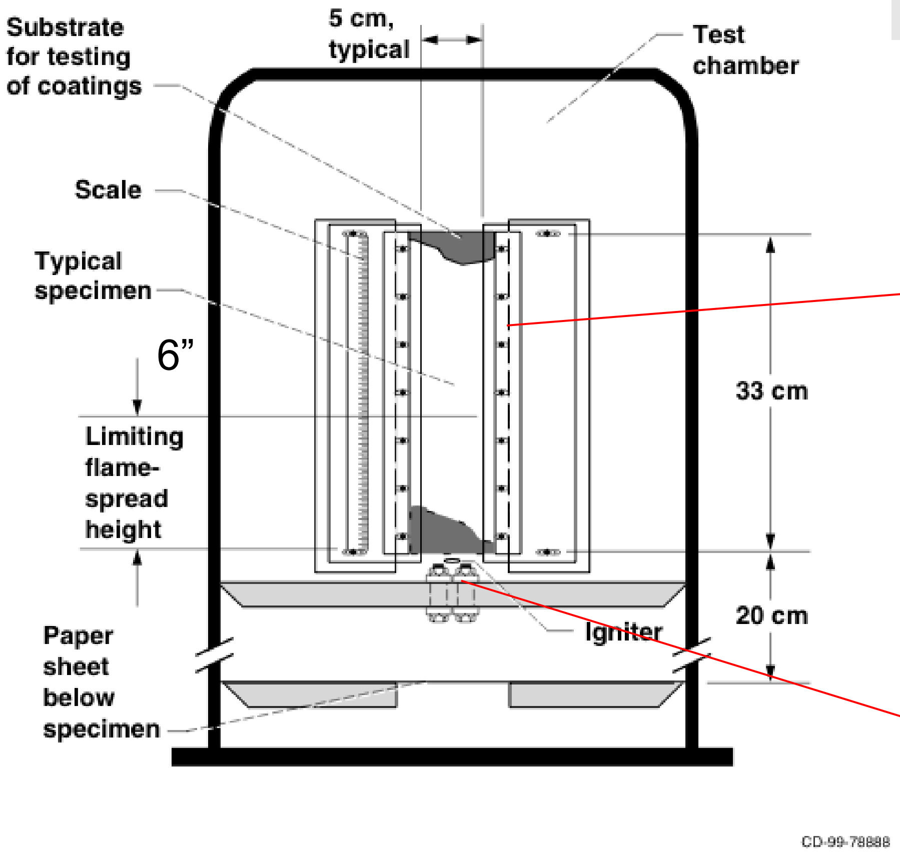
Totals:

Vented Mass O_2, g	10 to 16
Vented Mass N_2, g	40
Vented Mass CO_2, g	Up to 7
Vented Mass CO, g	Up to 0.2
Vented Mass H_2O, g	Up to 3
Soot vented	~ 0 (filtered)

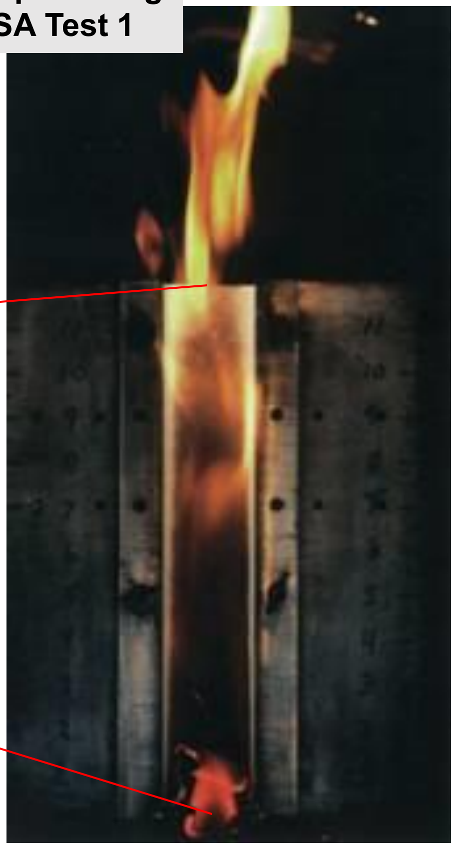
(There will be other trace products of combustion, typically in the ppm range or less.)

NASA STD-6001 Test 1

NASA currently tests materials for flammability using NASA STD-6001 Test 1, which is an upward burning test at the worst-case atmospheric conditions in which the material will be used. This has historically been 30% O_2, 10.2 psia (shuttle pre-EVA atm)



Sample failing NASA Test 1



A sample that burns more than 15 cm fails the STD-6001 Test 1.

The “burn length” as defined by the *consumed material* length.